APPLICATION OF INHIBITORS TO PREVENT SPONTANEOUS HEATING OF COAL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

MINING ENGINEERING

BY

DEBASIS RATH

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DEPARTMENT OF MINING ENGINEERING

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Under the guidance of

Prof. D.S. Nimaje

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National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the thesis entitled **"Application of inhibitors to prevent spontaneous heating of coal"** submitted by **Sri Debasis Rath** in partial fulfillment of the requirements for the award of Bachelor of Technology degree in Mining Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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ABSTRACT

The auto oxidation of coal without any external heat source ultimately leads to spontaneous combustion which is the main cause of coal mine accidents. It has been a major problem in the leading coal producing countries like China, USA and India. Therefore the assessment of this process is crucial to the mining industry. It depends upon different characteristics and properties of coal. Once the combustion of coal starts, it is very difficult to control the fire. Therefore it is quite essential to assess their degree of proneness so as to take necessary steps against the occurrence of fires in order to avoid loss of lives and property, sterilization of coal reserves and environmental pollution and raise concerns about safety and economic aspects of mining etc.

Twenty coal samples were collected from various coal fields such as MCL, NCL, NEC, BCCL, IISCO, TISCO. The project deals with effect of inhibitors on spontaneous heating liability of coal. The intrinsic properties as well as susceptibility indices of the coal samples were determined by following experimental techniques:

- Proximate analysis
- Flammability temperature

From the experiments carried out, it is found that, among the three inhibitors used, namely NaCl, EDTA and $CaCl_2$, NaCl is found to be the most effective in reducing the flammability temperature of coal.

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INTRODUCTION

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INTRODUCTION

1.1 General

The auto oxidation of coal is a complex physico-chemical process in which concurrent and instantaneous reactions takes place which become difficult to control, leading to the liberation of heat and ultimately resulting in fire. Mine fire explosions in Indian coalfields are generally caused by spontaneous combustion of coal despite various preventive measures being taken. The spontaneous combustion of coal varies over a wide range and it is important to assess their degree of proneness for taking preventive measures against the occurrence of fires to avoid the losses incurred by the organization. The rate of oxidation of coal gives the measure of susceptibility of coal towards spontaneous heating.

In order to find out the susceptibility of coal to spontaneous heating different methods have been adopted by various researchers of the world. A number of experiments have been done for assessing the spontaneous heating susceptibility of coal viz., Differential thermal analysis (Nimaje et al., 2010), Crossing point temperature method (Didari et al., 2000), Flammability temperature method (Nimaje et al., 2010), Wet oxidation potential method (Tarafdar et al., 1989). A number of approaches have been developed over the years to assess the degree of proneness of coal to spontaneous heating. This propensity to self-heating of coal also decides the incubation period of coal seams, which decide the size of the panel to be formed, which is a most important safety measure in mine planning. It is therefore imperative that the planners of a mine determine in advance the spontaneous heating susceptibility of the seam to be mined so that it is decided whether to extract the coal before the incubation period, or take precautionary measures to tackle this threat.

The rate of oxidation can be reduced by treatment with inhibitors and hence the fire risk can be reduced to a certain extent. The methods used to assess the susceptibility of coals towards spontaneous heating in the present study are Proximate analysis and Flammability temperature method.

1.2 Concept of Spontaneous Heating

Spontaneous combustion of coal is the process of self-heating ultimately resulting in its ignition without the application of external heat. When coal is exposed to air it absorbs oxygen at the exposed surface. Some fraction of the exposed surface absorbs oxygen at a faster rate than others which results in the formation of gases which are mainly CO, CO_2 and water vapour along with the evolution of heat during the chemical reaction. This process takes place at normal temperature, but it is slow and the heat evolved is not carried away by air. If the evolution of heat by oxidation is faster than the rate of dissipation of heat, then there is a gradual build-up of heat and temperature reaches the ignition point of coal which then catches fire.

The ignition temperature of bituminous coal is nearly 160-170°C and of anthracite coal nearly 185°C. A good air current will effectively prevent oxidation. Once the coal temperature reaches its ignition point, the air supply to it will only increase the combustion. The term spontaneous combustion expresses only a relative value which classifies coal as highly susceptible or not.

1.3 History of Spontaneous Heating

A fire in coal mines is a serious threat to the Indian coal mining industry. In India every year many mine fire incidents occur in the surface as well as underground due to spontaneous combustion.

This hazard has been existing in India for several years now. Analysis of the causes of the coal mine fires reveal that they start either from an open fire over the external mining agencies or originate due to varying nature of coal. The former is called open fire while the latter is the incipient fire. They endanger not only the lives of valuable men working in the mine but also cause serious economic losses to the organization affected by them. History of coal mine fires is dated back to the year 1865, when the first fire was first reported in Raniganj Coalfields. The open fire in in the mines not only causes environmental pollution by emission of huge quantities of steam, smoke and noxious gases but also poses a serious health hazards.

In Indian coal mines, 80% of the mine fires occur due to spontaneous combustion. The main aspect of a start of fire in India is because the coal seams are thicker and there is a tendency of spontaneous heating during the depillaring operation. The problem of extraction of thick seam and coal standing in pillars becomes a serious threat when coal is of high moisture, high

volatile matter and low ash content which is more liable to spontaneous combustion. It is impractical to be able to extract all the coal by caving method. Pillars standing for long time are liable to deteriorate and spilling may occur. If coal is heated to about 93°C and O_2 in the air is available, the oxidation will take place at an accelerated rate and if the heat of dissipation is less than the heat of accumulation then coal bed temperature increases, ultimately leading to fire.

1.4 Objective

The objective of the project is to measure the effectiveness of inhibitors in increasing the flammability temperature and thus determining the most effective one, by using the flammability temperature method. To achieve the above said objective, project is carried out in the following steps

- **Literature Review –** Review all the past works done by various researchers
- **Sample Collection –** Twenty coal samples were collected from various coal fields of India such as MCL, NCL, NEC, BCCL, IISCO, TISCO and prepared as per the Indian Standards
- **Experimentation –** The experiments were done in two stages:
    a. Determination of intrinsic properties of coal – proximate analysis.
    b. Determination of spontaneous heating susceptibility of coal – flammability temperature method.
- **Analysis –** Different graphs are plotted measuring the increase in flammability temperature over different concentrations of inhibitors with coal.

Chapter 2

LITERATURE REVIEW

CHAPTER – 2

LITERATURE REVIEW

2.1 Mechanism of spontaneous heating

The oxidation of coal, is exothermic in nature. The nature of the interaction between coal and oxygen at very low temperatures is fully physical (adsorption) and changes into a chemisorption form starting from an ambient temperature (Munzner and Peters, 1965; Banerjee, 1985 and Postrzednik et al., 1988). When coal is exposed to air it absorbs oxygen at the exposed surface. Some fraction of the exposed surface absorbs oxygen at a faster rate than others and the oxidation results in the formation of gases. Mainly CO, CO_2, water vapour along with the evolution of heat during the chemical reaction. Freshly exposed surfaces of coal consume oxygen at a relatively higher rate. It then decreases very slowly over time without causing much problem unless generated heat is allowed to accumulate in the environment. Under certain conditions, the accumulation of heat cannot be prevented, and with sufficient oxygen (air) supply, the process may reach higher stages.

The loose coal-oxygen-water complex formed during the initial stage (peroxy-complexes) decomposes above 70-85°C, yielding CO, CO_2 and H_2O molecules. The rate of chemical reactions and exothermicity change with the rise in temperature, and radical changes take place, starting at about 100°C, mainly due to loss of moisture (Oresko, 1959; Banerjee, 1985 and Handa et al., 1985). This process continues with the rise in temperature, yielding more stable coal-oxygen complexes until the critical temperature is reached. The ignition temperature of bituminous coal is nearly 160-170°C and of anthracite coal nearly 185°C. Once the coal reaches it ignition point, the air supply to it will only increase the combustion. The term spontaneous combustion expresses only a relative value which classifies coal as highly susceptible or not.

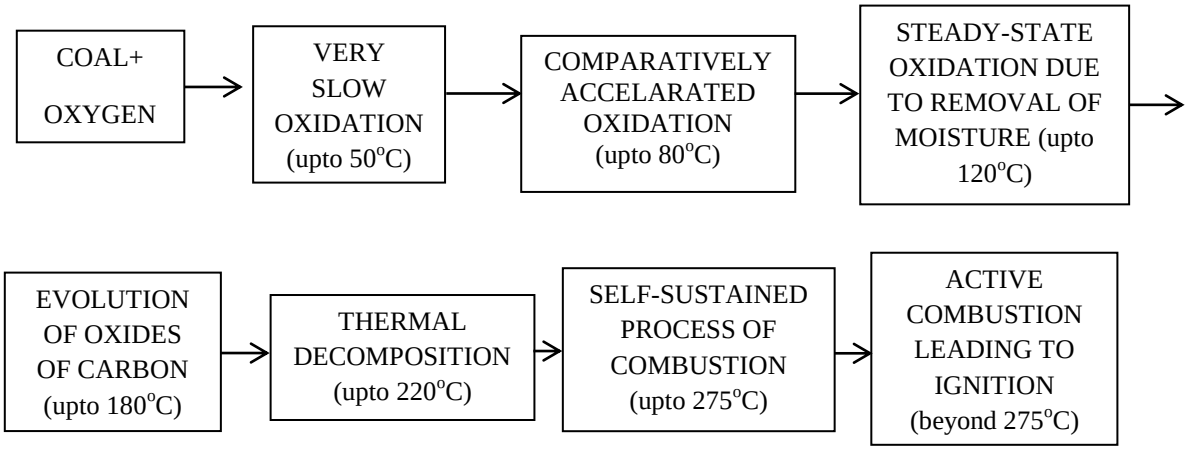

Fig. 2.1 Stages in Spontaneous Heating of Coal (Pal, 2012)

2.2 Factors affecting spontaneous heating

The main reason for the difficulties in understanding the mechanism of spontaneous combustion is the presence of many internal and external factors affecting the initiation and development of the phenomenon. These factors have been reviewed by various researchers (Kroger et al., 1962; Guney, 1968; Chamberlain et al., 1973; Feng et al., 1973; Beier, 1973; Kim, 1977; Banerjee,1982; Didari, 1988). The main factors which have significant effects on the process are summarized below:

2.2.1 Intrinsic factors – It is related to the nature of coal.

- Pyrites – As pyrite content increases the tendency of spontaneous heating increases.
- Inherent moisture – Changes in moisture content such as drying or wetting of coal have significant effects.
- Particle size and surface area – As particle size decreases the exposed surface area increases and the susceptibility increases.
- Coal rank and Petrographic constituents – Lower rank coals are more susceptible. Lignite and bituminous coals are more susceptible than anthracite coal.
- Chemical constituents – Ash content generally decreases liability for spontaneous heating but certain parts of ash such as lime, soda; iron compounds have accelerating effect whereas alumina and silica have retarding effects.
- Mineral matter – Some chemicals promote and others inhibit spontaneous heating.

2.2.2 Extrinsic factors – It **i**s related to atmospheric, mining and geological conditions.

- Temperature – Higher the surrounding temperature more is the rate of oxidation process and hence higher is the susceptibility of coal to spontaneous heating.
- Extraneous moisture – Evaporation of surface moisture leads to release of heat of wetting which adds to the temperature rise and increases susceptibility. Presence of atmospheric moisture increases rate of oxidation of coal.
- Oxygen concentration – Higher the oxygen concentration in the atmosphere more rapid is the oxidation process.
- Coal seam and surrounding strata – Presence of faults that lead to the passage of air and oxygen to the heating are generally increase the rate of heating.
- Method of working, ventilation and air flow rate – Mining methods such as bord and pillar mining that leaves behind some pillars make the coal more susceptible to spontaneous heating than longwall methods. Air flow rate also controls heating to a large extent. If an ideal flow rate is maintained then it helps in dissipation of heat but if too much of air is flowing then it lazes the heat and increases the heating.
- Timbering, roadways, bacteria and barometric pressure – Presence of timbers in the mines leads to the danger of catching of fire which gives the heat required for spontaneous heating of coal. Bacterial decomposition of coal and other wood products due to presence of Thiobacilli also releases some amount of heat which increases susceptibility.

These factors can be further classified into :-

- **Mining Factors (Morris et al., 1986)**

i) Mining Methods
ii) Rate of Advance
iii) Pillar Conditions
iv) Roof Conditions
v) Crushing
vi) Packing
vii) Effect of Timber
viii) Roadways
ix) Leakage
x) Multi Seam Workings
xi) Coal Losses
xii) Main Roads
xiii) Worked-out areas
xiv) Heat from Machines
xv) Stowing
xvi) Ventilations Pressure
xvii) Barometric Pressure
xviii) Change in Humidity

- **Geological Factors (Morris et al., 1986)**

  i) Seam thickness
  ii) Seam gradient
  iii) Caving characteristics
  iv) Faulting
  v) Coal Outbursts
  vi) Friability
  vii) Depth of cover
  viii) Geothermal Gradient

- **Seam Factors (Morris et al., 1988)**

  i) Rank
  ii) Petrographic Composition
  iii)Temperature
  iv) Available air
  v) Particle Size/Surface Area
  vi) Moisture
  vii) Sulphur
  viii) Ash/Mineral Matter
  ix) The effect of previous oxidation or heating
  x) Physical Properties
  xi) Heating due to earth movement
  xii) Bacteria
  xiii) Pyrite Content
  xiv) Thermal Conductivity

2.3 Controlling spontaneous combustion (Phillips et al., 2009)

Effective control of spontaneous combustion can be achieved by using a combination of techniques. The control measures that can be applied in different coalfields can be listed in three groups:

1. Control measures to reduce or eliminate oxygen from the process
   - Sealing agents
   - Dozing over
   - Buffer blasting
   - Cladding of the highwall
2. Control measure to reduce the temperature and hence the reaction rate
   - Water cannons onto the highwall and in front of the dragline and during coaling.
   - Nitrogen injection into old workings.
   - Carbon dioxide injection into old workings.
3. Removal of the fuel
   - Excavation of hot or burning material.

The efficacy of these control measures is dependent on individual situations such as mining layouts and the extent of the spontaneous combustion problem. Small-scale fires in stockpiles or areas exposed by mining may be extinguished or controlled by flooding with water or by

removing the burning material. Caution must be taken when fighting spontaneous combustion fires with water as a dangerous reaction between the water and the heated coal can occur.

In attempting to control heating by spraying or injecting water, it is possible to produce water gas, which is a mixture of carbon monoxide and hydrogen. Both these gases are highly flammable and are produced in the reaction between hot carbon and water. The chemical reaction for this is:

$$C + H_2O = CO + H_2$$

Because of the wide explosive limits of water gas (4% to 74%), the highly toxic nature of carbon monoxide and the presence of a source of ignition, production of water gas should be avoided as much as possible. The situation is made more hazardous by the large volumes of gas and associated steam violently produced from the solid-liquid reaction. Thus water should only be used to control heating if the heating can be inundated rapidly, limiting the amount of water gas produced and excluding air. Even in surface operations where the risk of explosion is lower, crews fighting spontaneous combustion by using water should monitor carbon monoxide and hydrogen levels.

Fire fighting foam has been used as an alternative to water with some success. A more widely accepted method is for the material to be spread out to cool and the ash disposed of in a manner suited to its chemical and physical properties, i.e. used as construction material or buried. Speed and safety are essential in such operations. Protective clothing and breathing apparatus should be provided and the equipment must be suitable for the particular work (i.e. no rubber tyres or petrol driven equipment).

Inhibitors can also be used to inhibit the spontaneous heating of coal (Ramlu, 2007). The antipyrogenes or inhibitors can be used in following ways:

1) Formation of a protective surface coating both on the macropore and micropore surface, resulting in the formation of a heat insulating layer.
2) Formation of a layer which increases the thermal conductivity of the coal and thereby enhances the rate of heat removal from local heat spots.
3) Formation of a layer which consumes heat during its decomposition while the coal is in the process of oxidation before reaching the critical temperature range.
4) Formation of layer, preferably gaseous, which acts a s a diluent and removes heat
5) Chain breaking reaction which retards oxidation.

Many kinds of inhibitors – solid, liquid and gaseous – have been tried by many investigators in India, USA, USSR, Germany and a few other countries for fighting incipient and open

fires on the surface with a fair amount of success. Special mention may be made of Calcium Hydroxide, Sodium Chloride, Calcium Bicarbonate, Calcium Chloride, Montan Powder, Ammonium Borate, Ammonium Chloride and Boric Acid.

2.4 National and International status

Ghosh (1985) made an attempt to evolve a method to identify degree of proneness of coal to spontaneous combustion. It has been seen that if pyrite is present in a coal in finely divided form, the proneness of coals towards spontaneous combustion increases; and the temperature of a coal bed increases if water is added to it, which tends to indicate that water spraying or even flooding cannot be considered as an effective measure to control spontaneous combustion. Moreover, it was also suggested that if coal is chilled (to −193°C) the micropores and microcracks in the coal are possibly contracted. Atmospheric oxygen is less likely to enter the coal through these micropores and microcracks; and hence chances of spontaneous combustion due to auto - oxidation are diminished.

Gouws et al. (1990) designed an adiabatic calorimeter to enable the spontaneous combustion propensity of coal to be established. Various indicators of self-heating potential, such as total temperature rise, initial rate of heating, minimum self-heating temperature, and kinetic constants were investigated. Results obtained from the adiabatic tests were compared with the results of crossing-point temperature determinations and differential thermal analysis (DTA) tests for the same coals, with a view to formulating a mathematically consistent spontaneous combustion liability index. This paper describes the major components of the adiabatic calorimeter.

Sujanti et al. (1998) A laboratory investigation was made to measure the effect of inorganic matter on spontaneous combustion behaviour of coal. Fourteen samples were prepared and doped with 11 inhibitors. Each of the samples was then tested in an isothermal reactor to obtain its critical ambient temperature, above which spontaneous combustion occurs. Potassium chloride, Montan powder, and sodium chloride were found to be the most effective inhibitors, followed by magnesium acetate, and calcium chloride.

Watanabe et al. (2001) The influence of inherent and added inorganic matter on low-temperature oxidation reactions of coal and the effectiveness of the inhibitors to affect the oxidation reactions are examined in this paper. Of the seven inhibitors used, $Cu(Ac)_2$, KAc,

and NaAc were found to promote the oxidation reaction, while NaCl, $CaCl_2$, and $Mg(Ac)_2$ inhibit the reaction.

Panigrahi et al. (2005) A laboratory study was carried out to test suitable inhibitors to inhibit the spontaneous heating characteristics of coal. The experimental study indicates that 5% aqueous solution of some of these inhibitors show satisfactory results in inhibiting the spontaneous heating characteristics of these samples.

Singh et al. (2007) observed in opencast mines, coal immediately oxidises and catches fire due to the intrinsic characteristics of coal, such as low rank, high moisture, high volatile matter, and presence of sulphur in the form of pyrites, low crossing point temperature (CPT) and ignition point temperature (IPT) value and less incubation period. In opencast mines, when the coal benches are left idle for a longer time, heat accumulation takes place in favourable conditions and sometimes leads to fire. The purpose of this paper is to present the different successful case studies regarding the safety management of open pit coal mines from occurrences of spontaneous heating.

Nimaje et al. (2010) made thermal studies on spontaneous heating of coal. Of all the experimental techniques developed, thermal studies play an important and dominant role in assessing the spontaneous heating susceptibility of coal. They made an overview of thermal studies carried out by different researchers across the globe for determination of spontaneous heating of coal and revealed that lot of emphasis on experimental techniques is necessary for evolving appropriate strategies and effective plans in advance to prevent occurrence and spread of fire.

Shui-jun et al. (2011) studied the influence of organic and inorganic additive to coal combustion characteristic; a self-made small-sized experiment platform and advanced gas analyzer PG-250A were used and the concentration changes of CO released by three kinds of coals with different properties in the oxidation process of low temperature (150^oC) were determined continuously before and after adding new type Ammonia-free Gel, $MgCl_2$ and Antioxidant A. Study indicates that: Ranging the inhibitors by their inhibitory effect form superior to inferior, three inhibitors are in turn Ammonia-free Gel 2, $MgCl_2$ and Antioxidant A.

Chapter 3

EXPERIMENTAL TECHNIQUES

CHAPTER – 3

EXPERIMENTAL TECHNIQUES

To study the effects of various parameters of coal that affect the spontaneous heating tendency of coal, the following experiments are needed to be carried out for studying the intrinsic properties of coal:

- Proximate analysis
- Ultimate analysis
- Petrographic analysis
- Calorific value

To study the susceptibility of coal the following experiments are needed to be carried out:

- Wet oxidation potential
- Flammability temperature
- Crossing point temperature
- Olpinski index
- Critical air blast
- Differential thermal analysis
- Differential scanning calorimetry

3.1 SAMPLE COLLECTION AND PREPARATION

It is the process by which the physical and chemical properties of the mineral or ore can be ascertained with the desired accuracy. It is the process of collecting the small portion of a whole such that consistence of that portion represents that of a whole.

Different types of sampling are:

- Channel sampling
- Chip sampling
- Grab sampling
- Bulk sampling
- Drill hole sampling

Chip sampling is done in hard ores where it is difficult to cut the channels. It can be taken in case of uniform ores and where the rock structures are independent of the values. The sample is collected by breaking of small equal sized chips from a face at points equally spaced both vertically and horizontally.

Grab sampling is applied to the broken ore in the stope or at the face, ore transported. But it is unreliable as estimation of the volume of broken ore will be inaccurate. Grab sampling of tubs or ships is however more representations since samples are collected from units of regular volume.

Bulk sampling is done where conventional sampling methods lags behind. Bulk samples eliminate the effect of irregular distribution of value or minor.

For the project work, the samples have been collected by channel sampling which is the most common method followed.

3.1.1 Channel sampling (IS 436 Part I/Section I - 1964)

The section of seam to be sampled shall be exposed from the roof to the floor. The seam sample shall, be taken in a channel representing the entire cross-section of the seam having the dimensions of 30 x 10 cm, that is, 30 cm in width and 10 cm in depth. For this purpose, two parallel lines, 30 cm apart end at right angles to the bedding planes of the seam shall be marked by a chalked string on the smooth, freshly exposed surface of the seam. Obvious dirt bands exceeding 10 cm in thickness shall be excluded. The channel between the marked chalk lines in the seam shall be cut to a depth of 10 cm and the coal sample collected on a clean strong clot h or tarpaulin placed immediately at the bottom so that the chances of pieces flying off during excavation of coal are minimized.

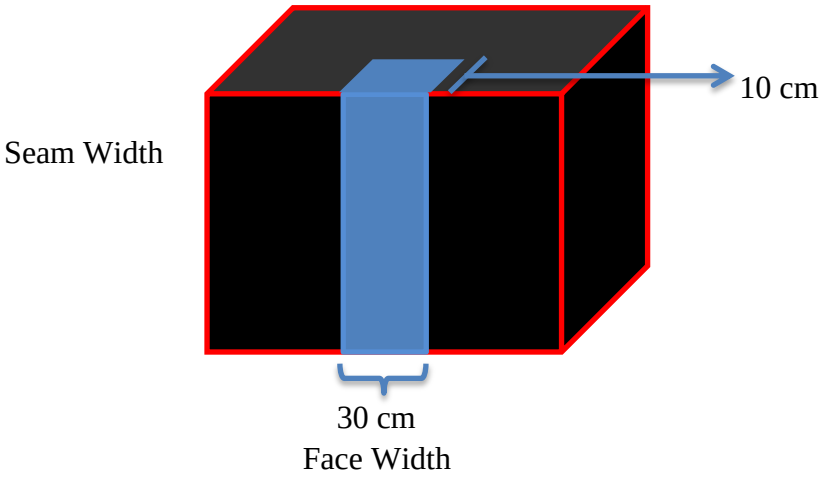

Fig. 3.1 Channel Sampling (Bharath, 2010)

3.1.2 Sample preparation (IS 436 Part 1/Section 1-1964 and IS 436 Part II-1965)

The samples received from the field via channel sampling are crushed in the laboratory as per the experimental requirements. The crushed sample is then sieved to required sizes and stored in air tight polythene packets. These packets are then stored in air tight plastic containers for further experimental use.

3.2 METHODS FOR DETERMINING INTRINSIC PROPORTIES OF COAL

3.2.1 Proximate analysis (IS 1350 Part I -1984)

The objective of coal ultimate analysis is to determine the amount of fixed carbon (FC), volatile matters (VM), moisture content (MC), and ash (A) within the coal sample. The variables are measured in weight percent (wt. %) and are calculated in several different basis.

- ar (as-received) – puts all variables into consideration and uses the total weight as the basis of measurement.
- ad (air-dried) – neglects the presence of moistures other than inherent moisture.
- db (dry-basis) – leaves out all moistures, including surface moisture, inherent moisture, and other moistures daf (dry, ash free) – neglects all moisture and ash constituent in coal.
- dmmf (dry, mineral-matter-free) – leaves out the presence of moisture and mineral matters in coal

Plate 3.1 Moisture Oven

Plate 3.2 Muffle Furnace

3.2.1.1 Moisture Content

Procedure:

- Take 1 g of – 72 mesh (BSS) coal sample in a glass crucible.
- Put it in a furnace at 110^0C and leave it for 90 minutes.
- Remove the sample after 90 minutes and weigh the glass crucible again.
- Calculate the moisture content by using the following formula

  Total moisture content of the original sample,

  $$MC = (X - Y)/X * 100$$

  Where,

  X = Initial mass of the coal sample before heating (g)

  Y = Final mass of coal sample after heating (g)

3.2.1.2 Ash

Procedure:

- Take 1g of -72 mesh (BSS) coal sample in a silica crucible
- Heat the sample in a muffle furnace at 450°C for 30 minutes and then further heat it for 1 hour with temperature rising from 450 to 850°C.
- Remove the silica crucible and then allow it to cool in a dessicator for 15 minutes and weigh the crucible again.
- Obtain ash content by the formula

  $$\text{Ash percentage, } A = 100 * (Z - X)) / (Y - X)$$

  Where,

  X = Mass of crucible (g)

  Y = Mass of crucible and sample (g)

  Z = Mass of crucible and ash (g)

3.2.1.3 Volatile matter

Procedure:

- Take 1 g of -72 mesh (BSS) coal sample in a crucible and put the lid.
- Put the crucible in a furnace maintained at 925°C for 7 minutes exactly. Take out the crucible and weigh it again.
- Calculate the volatile matter content by using the relation

Volatile matter percentage, V = (100 * (Y – Z) / (Y – X))

Where,

X = Mass of empty crucible and lid

Y = Mass of crucible plus lid and sample before heating

Z = Mass of crucible plus lid and sample after heating

3.2.1.4 Fixed carbon

It is determined by subtracting the sum of all the above parameters and is given as

Fixed Carbon, FC = 100 – (M + V + A)

Where,

M = Moisture content

V = Volatile matter content

A = Ash content

Calculation on different basis:

- **Dry Basis**

$$\text{Ash} = \frac{\%\text{ash on air dried basis}}{100 - \%\text{moisture}} \times 100$$

$$\text{VM} = \frac{\%\text{volatile matter on air dried basis}}{100 - \%\text{moisture}} \times 100$$

FC = 100 – (Ash + VM on % dry basis)

- **Dry Ash Free Basis**

$$\text{VM} = \frac{\%\text{volatile matter on air dried basis}}{100 - (\text{moisture} + \text{ash})} \times 100$$

FC = 100 – VM (on % daf basis)

- **Dry Mineral Matter Free Basis**

$$\text{VM} = \frac{\%\text{volatile matter on air dried basis - 0.1 ash on air dried basis}}{100 - (\text{moisture} + 1.1\text{ash})\text{on \% air dried basis}} \times 100$$

FC = 100 – VM(on % dmmf basis)

3.3 METHODS FOR DETERMINING SPONTANEOUS HEATING SUSCEPTIBILITY OF COAL

3.3.1 Flammability temperature method (Nimaje et al., 2010)

The setup for the determination of the flammability temperature of coal consists of vertical tubular furnace of internal diameter 50mm, length 300mm, open at both ends, a dust dispersing unit, a solenoid valve a reservoir for air, a mercury manometer, a drying tower and an aspirator bulb. Coal dust sample is kept in the helical dust disperser. Air from the reservoir is made to pass through the disperser and on emergency from the divergent mount, forms a uniform dust-air mixture inside the furnace. The minimum temperature at which this mixture catches fire, which is indicated by the appearance of flame coming out of the bottom of the tubular furnace, is the flammability temperature of the coal dust.

Procedure:

- Take 200 mg of coal sample of -200 mesh size (BSS) in a helical tube.
- Prepare a set of doped samples by adding NaCl, to coal at a concentration of 5%, 10%, 15%, 20% (%wt.) and so on.
- Maintain mercury column difference of 8 cm by aspirator bulb and turn off the tap
- At desired temperature of furnace, switch on the solenoid valve, which allows the air to pass through it very fast and find out the status of coal sample (spark, smoke or flame).
- If flame appears then find out the exact temperature in lower temperature range by trial and error method, if not, then go for higher temperature range.
- After finding the flammability temperature of the coal sample, repeat the above procedure for the doped samples. Note down all the readings.
- Then repeat the above procedure by mixing coal similarly with EDTA (Ethylene Diammine Tetra Acetate) and anhydrous Calcium Chloride ($CaCl_2$).

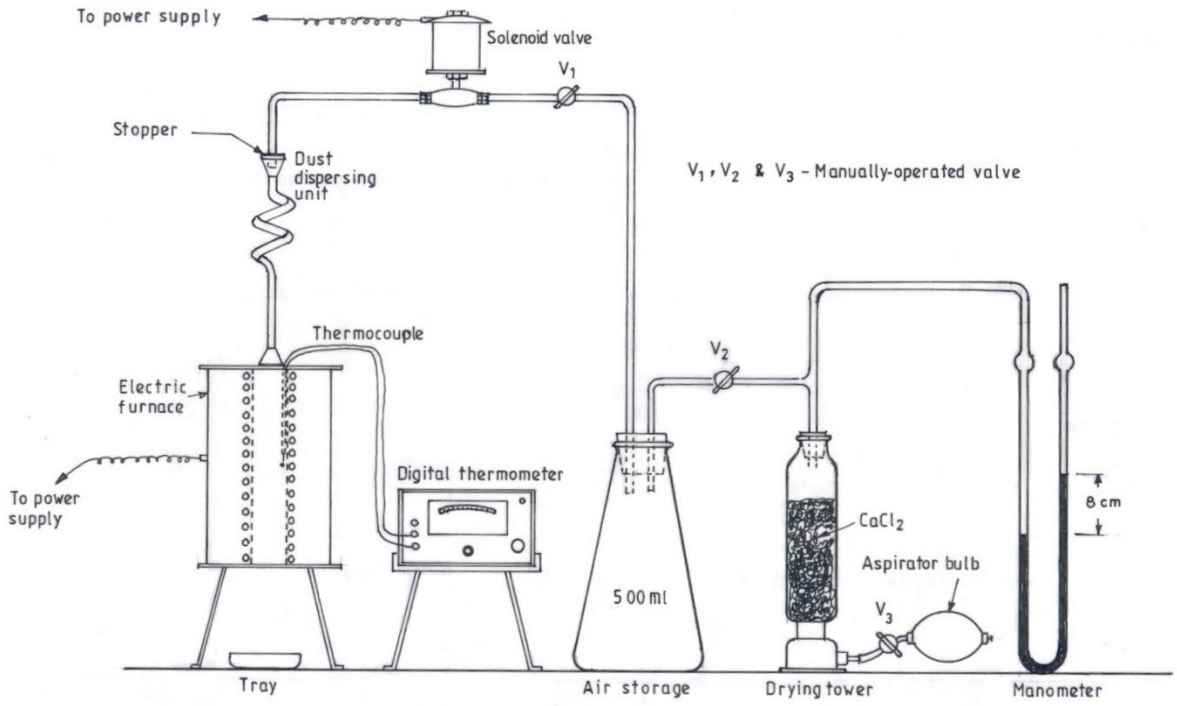

Fig. 3.2 Schematic Diagram of Flammability Temperature Apparatus (Nimaje et al., 2010)

Chapter 4

RESULTS

CHAPTER – 4

RESULTS

4.1 Abstract of experimental techniques

1. Proximate analysis

A. Determination of moisture

- Amount of coal : 1 g coal
- Size of coal : - 212 micron (-72 mesh BSS)
- Heating time : 1.5 hours at 108 ± 2° C

B. Determination of volatile matter

- Amount of coal : 1 g of coal
- Size of coal : - 212 micron (-72 mesh BSS)
- Heating time : 7 minutes at 925 ± 10° C

C. Determination of ash

- Amount of coal : 1 g of coal sample
- Size of coal : - 212 micron (-72 mesh BSS)
- Heating time : 30 minutes at 450°C and 60 minutes at 850°C

2. Flammability Temperature

- Amount of coal : 200 mg of coal sample
- Size of coal : - 72 micron (-200 mesh BSS)
- System : Coal + Air
- Pressure of air : 8 cm of Hg

Table 4.1 List of Coal Samples

Sl No.	Sample Code	Name of Organization
1	NCL - 1	NCL, Coal India Limited, Madhya Pradesh
2	NCL - 2	
3	MCL - 1	MCL, Coal India Limited, Odisha
4	MCL - 2	
5	MCL - 3	
6	MCL – 4	
7	MCL – 5	
8	MCL – 6	
9	MCL – 7	
10	MCL - 8	
11	NEC – 1	NEC, Coal India Limited, Assam
12	NEC - 2	
13	NEC – 3	
14	NEC – 4	
15	NEC – 5	
16	NEC – 6	
17	IISCO – 1	IISCO, Dhanbad, Jharkhand
18	IISCO – 2	
19	BCCL - 1	BCCL, Coal India Limited, Dhanbad, Jharkhand
20	TISCO - 1	TISCO, Dhanbad, Jharkhand

Table 4.2 Results of proximate analysis parameters of coal

Sl No	Sample Code	Basis	Moisture %	Ash %	VM %	FC %
1	NCL – 1	air dried	7.94	58.47	28.4	5.19
		dry	---	63.51	30.85	5.64
		daf	---	---	84.55	15.55
		dmmf	---	---	81.29	18.71
2	NCL – 2	air dried	4.03	38.06	31.21	26.7
		dry	---	39.66	32.52	27.8
		daf	---	---	53.9	46.11
		dmmf	---	---	50.7	49.3
3	MCL – 1	air dried	4.13	61.48	28.17	6.2
		dry	---	64.15	29.38	6.47
		daf	---	---	81.96	18.04
		dmmf	---	---	78.03	21.97
4	MCL – 2	air dried	3.42	57.28	31.75	7.558
		dry	---	59.3	32.87	7.83
		daf	---	---	80.77	19.23
		dmmf	---	---	77.49	22.51
5	MCL – 3	air dried	2.81	13.46	30.19	53.556
		dry	---	13.83	31.06	55.1
		daf	---	---	36.05	63.95
		dmmf	---	---	35.01	64.99
6	MCL – 4	air dried	2.625	55.5	20.92	20.955
		dry	---	57	21.48	21.5
		daf	---	---	49.96	50.04
		dmmf	---	---	42.31	57.69
7	MCL – 5	air dried	3.89	16.2	35.55	44.36
		dry	---	16.86	36.99	46.2
		daf	---	---	44.49	55.51
		dmmf	---	---	43.34	56.66

Sl No	Sample Code	Basis	Moisture %	Ash %	VM %	FC %
8	MCL – 6	air dried	0.925	63.3	19.78	15.995
		dry	---	63.89	19.96	16.1
		daf	---	---	55.29	44.71
		dmmf	---	---	45.68	54.32
9	MCL – 7	air dried	2.765	10.4	34.94	51.895
		dry	---	10.7	35.93	53.4
		daf	---	---	40.24	59.76
		dmmf	---	---	39.51	60.49
10	MCL – 8	air dried	1.36	65.45	26.49	6.7
		dry	---	66.35	26.86	6.79
		daf	---	---	79.81	20.19
		dmmf	---	---	74.85	25.15
11	NEC - 1	air dried	4.537	50.33	29.38	15.753
		dry	---	52.72	30.78	16.5
		daf	---	---	65.1	34.9
		dmmf	---	---	60.72	39.28
12	NEC – 2	air dried	4.389	52.7	31.16	11.751
		dry	---	55.12	32.59	12.3
		daf	---	---	72.62	27.38
		dmmf	---	---	68.78	31.22
13	NEC – 3	air dried	4.059	54.12	30.19	11.631
		dry	---	56.41	31.47	12.1
		daf	---	---	72.19	27.81
		dmmf	---	---	68.05	31.95
14	NEC – 4	air dried	2.356	55.45	30.98	11.214
		dry	---	56.79	31.73	11.5
		daf	---	---	73.42	26.58
		dmmf	---	---	69.4	30.6

Sl No	Sample Code	Basis	Moisture %	Ash %	VM %	FC %
15	NEC – 5	air dried	2.153	54.44	29.91	13.497
		dry	---	55.64	30.57	13.8
		daf	---	---	68.91	31.09
		dmmf	---	---	64.45	35.55
16	NEC – 6	air dried	2.533	56.3	32.86	8.307
		dry	---	57.76	33.71	8.52
		daf	---	---	79.82	20.18
		dmmf	---	---	76.62	23.38
17	IISCO – 1	air dried	0.822	53.37	14.24	31.568
		dry	---	53.81	14.36	31.8
		daf	---	---	31.09	68.91
		dmmf	---	---	22	78
18	IISCO – 2	air dried	0.974	54.37	16.7	27.956
		dry	---	54.9	16.86	28.2
		daf	---	---	37.4	62.6
		dmmf	---	---	28.72	71.28
19	BCCL - 1	air dried	1.399	51.48	19.3	27.821
		dry	---	52.21	19.57	28.2
		daf	---	---	40.96	59.04
		dmmf	---	---	33.72	66.28
20	TISCO – 1	air dried	1.445	50.86	18.05	29.645
		dry	---	51.61	18.31	30.1
		daf	---	---	37.84	62.16
		dmmf	---	---	30.43	69.57

Where,

VM = Volatile Matter

FC = Fixed Carbon

Table 4.3 Results of flammability temperature of coal

Sl. No.	Sample Code	Flammability Temperature (^{o}C)
1	NCL - 1	520
2	NCL - 2	540
3	MCL - 1	525
4	MCL - 2	515
5	MCL - 3	530
6	MCL – 4	500
7	MCL – 5	520
8	MCL – 6	535
9	MCL – 7	510
10	MCL - 8	530
11	NEC – 1	520
12	NEC - 2	540
13	NEC – 3	550
14	NEC – 4	555
15	NEC – 5	560
16	NEC – 6	540
17	IISCO – 1	580
18	IISCO – 2	585
19	BCCL - 1	590
20	TISCO - 1	595

Table 4.4 Results of flammability temperature of coal with NaCl

Sl. No.	Sample Code	Flammability Temperature (^oC)	With NaCl			
			5%	10%	15%	20%
1	NCL - 1	520	530	535	540	--
2	NCL - 2	540	550	560	570	--
3	MCL - 1	525	535	540	545	530
4	MCL - 2	515	525	530	535	--
5	MCL - 3	530	540	545	550	525
6	MCL – 4	500	510	515	520	--
7	MCL – 5	520	525	530	535	--
8	MCL – 6	535	545	550	555	--
9	MCL – 7	510	515	520	525	--
10	MCL - 8	530	535	540	545	--
11	NEC – 1	520	530	535	540	510
12	NEC - 2	540	550	555	560	--
13	NEC – 3	550	560	555	560	--
14	NEC – 4	555	570	575	580	575
15	NEC – 5	560	570	575	580	--
16	NEC – 6	540	550	555	560	--
17	IISCO – 1	580	590	595	600	--
18	IISCO – 2	585	590	595	600	--
19	BCCL - 1	590	600	605	615	--
20	TISCO - 1	595	600	605	610	--

Table 4.5 Results of flammability temperature of coal with EDTA

Sl. No.	Sample Code	Flammability Temperature (^oC)	With EDTA		
			5%	10%	15%
1	NCL - 1	520	525	530	510
2	NCL - 2	540	545	550	540
3	MCL - 1	525	525	530	535
4	MCL - 2	515	520	525	510
5	MCL - 3	530	535	540	545
6	MCL – 4	500	505	510	515
7	MCL – 5	520	525	530	520
8	MCL – 6	535	540	545	525
9	MCL – 7	510	515	520	500
10	MCL - 8	530	535	540	490
11	NEC – 1	520	525	530	510
12	NEC - 2	540	545	550	510
13	NEC – 3	550	555	560	520
14	NEC – 4	555	560	565	--
15	NEC – 5	560	565	570	--
16	NEC – 6	540	545	550	--
17	IISCO – 1	580	585	590	--
18	IISCO – 2	585	590	595	--
19	BCCL - 1	590	595	600	--
20	TISCO - 1	595	600	605	--

Table 4.6 Results of flammability temperature of coal with $CaCl_2$

Sl. No.	Sample Code	Flammability Temperature (^oC)	With $CaCl_2$			
			5%	10%	15%	20%
1	NCL - 1	520	525	530	535	540
2	NCL - 2	540	555	560	545	--
3	MCL - 1	525	530	535	510	--
4	MCL - 2	515	520	525	500	--
5	MCL - 3	530	535	540	545	--
6	MCL – 4	500	510	515	520	--
7	MCL – 5	520	525	530	535	--
8	MCL – 6	535	540	550	520	--
9	MCL – 7	510	515	520	--	--
10	MCL - 8	530	540	545	550	--
11	NEC – 1	520	525	530	500	--
12	NEC - 2	540	545	550	555	540
13	NEC – 3	550	555	560	--	--
14	NEC – 4	555	565	570	550	--
15	NEC – 5	560	570	575	--	--
16	NEC – 6	540	550	555	560	--
17	IISCO – 1	580	585	590	--	--
18	IISCO – 2	585	590	600	610	--
19	BCCL - 1	590	600	605	--	--
20	TISCO - 1	595	605	610	615	--

Chapter 5

DISSCUSSION and CONCLUSION

Chapter – 05

Discussion and Conclusion

5.1 Discussion

Results of proximate analysis and flammability temperature method are tabulated and graphs are drawn so as to compare the effectiveness of an inhibitor in increasing the flammability temperature, thereby reducing its susceptibility towards spontaneous heating. Following are the inferred statements obtained from the graph analysis.

- Sample MCL – 8 has the highest ash content (65.45%) and also lowest fixed carbon (6.7). High ash content coals tend to show less susceptibility to spontaneous heating.
- Samples from IISCO are found to have very low moisture content (0.8 to 0.9) but are high in ash content (53 to 54) and hence they are less susceptible to spontaneous heating.
- Sample NEC – 1 has highest moisture content (4.5) and volatile matter is 24.8%, thus showing that it is moderately susceptible to spontaneous heating.
- Samples from NEC and MCL have flammability temperature in the range of 500 to 540^{o}C.
- Samples from NEC have flammability temperature in the range of 520 to 560^{o}C.
- Samples from IISCO, BCCL and TISCO have flammability temperature in the range of 580 to 595^{o}C.
- There was a substantial rise in flammability temperature by mixing upto 15% (by wt.) NaCl with coals of NCL in comparison to 10% EDTA and $CaCl_2$.
- On mixing inhibitors with coal samples from MCL, positive result was obtained for the 5, 10 and 15% (by wt.) concentration of NaCl. There was a decrease in temperature after mixing more than 10% (by wt.) in case of EDTA and $CaCl_2$.
- There was a gradual increase in temperature when inhibitors were added upto 10% (by wt.) to coal samples from NEC, IISCO, BCCL and TISCO. But beyond that only NaCl tends to increase the flammability temperature of the coal sample while EDTA and $CaCl_2$ showed varying results with the samples.

5.2 Conclusion

EDTA and $CaCl_2$ show a rise in flammability temperature when 10% (by wt.) is mixed with coal and tested. On adding more EDTA or $CaCl_2$, their effect becomes unpredictable because in some cases, when coal was mixed with more than 10% of EDTA or $CaCl_2$, it was seen that coal catches fire earlier than its expected flammability temperature. From the above discussion, it can be inferred that NaCl showed an increase in flammability temperature when mixed upto 15% (by wt.). NaCl is not only the most cost effective inhibitor which possesses no threat to human health or environment but also tends to increase the flammability temperature of coal to a certain extent.

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APPENDIX - A

Comparison of Results of Flammability Temperature of coal mixed with inhibitors

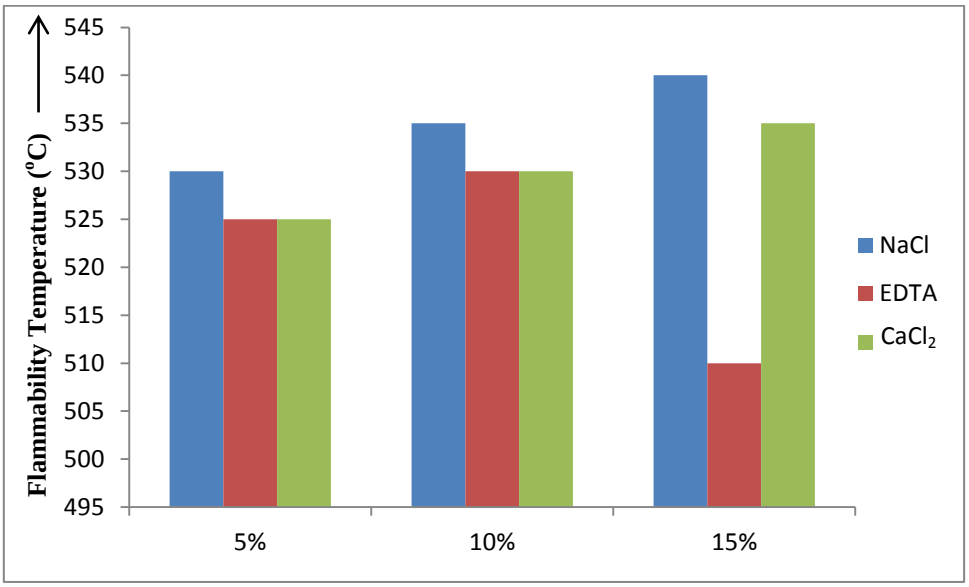

Fig A-1. Effect of different inhibitors on Flammability Temperature of NCL - 1

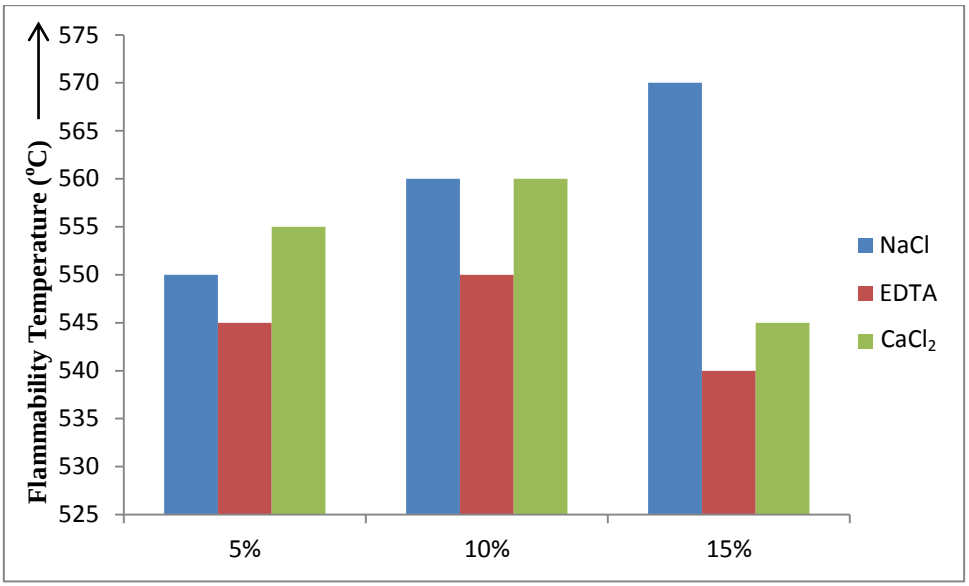

Fig A-2. Effect of different inhibitors on Flammability Temperature of NCL - 2

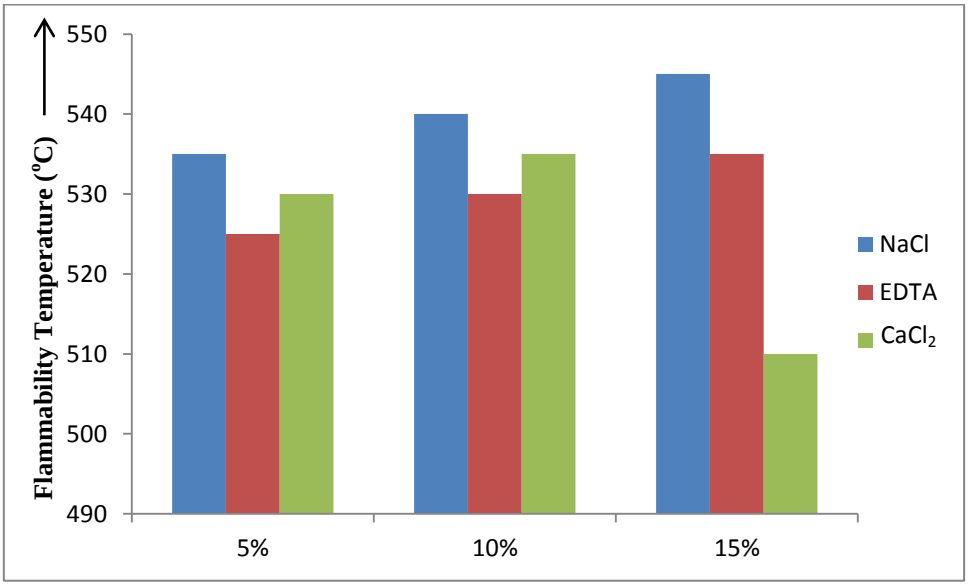

Fig A-3. Effect of different inhibitors on Flammability Temperature of MCL - 1

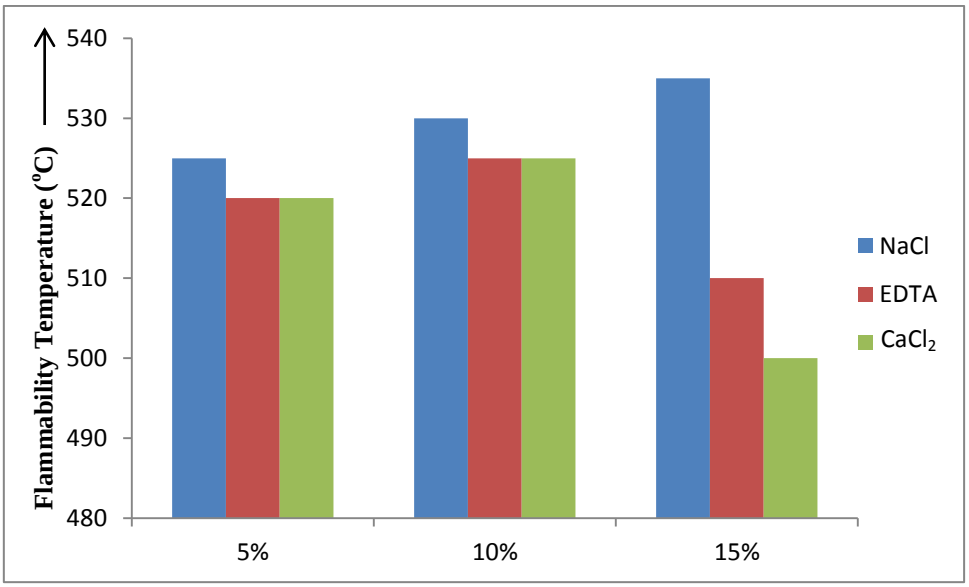

Fig A-4. Effect of different inhibitors on Flammability Temperature of MCL - 2

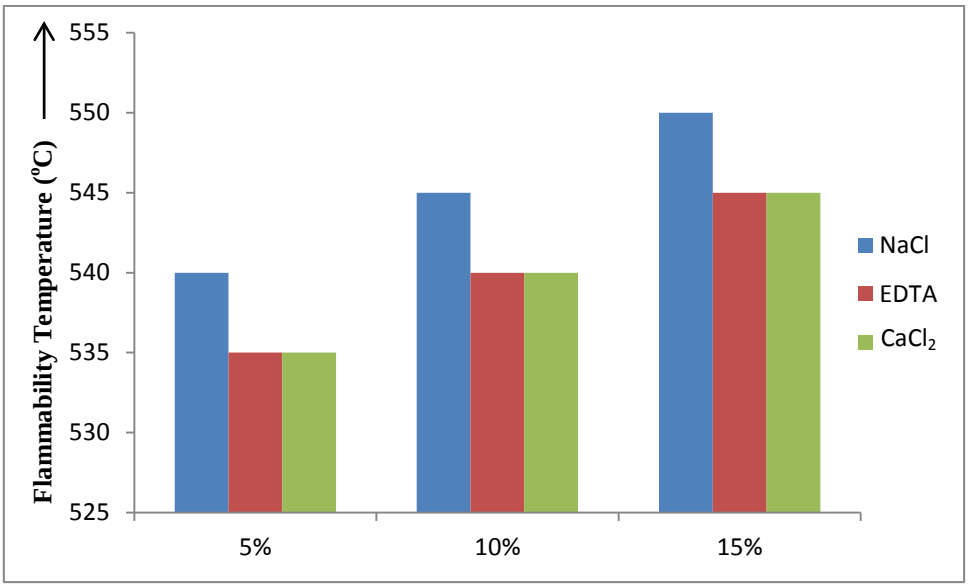

Fig A-5. Effect of different inhibitors on Flammability Temperature of MCL - 3

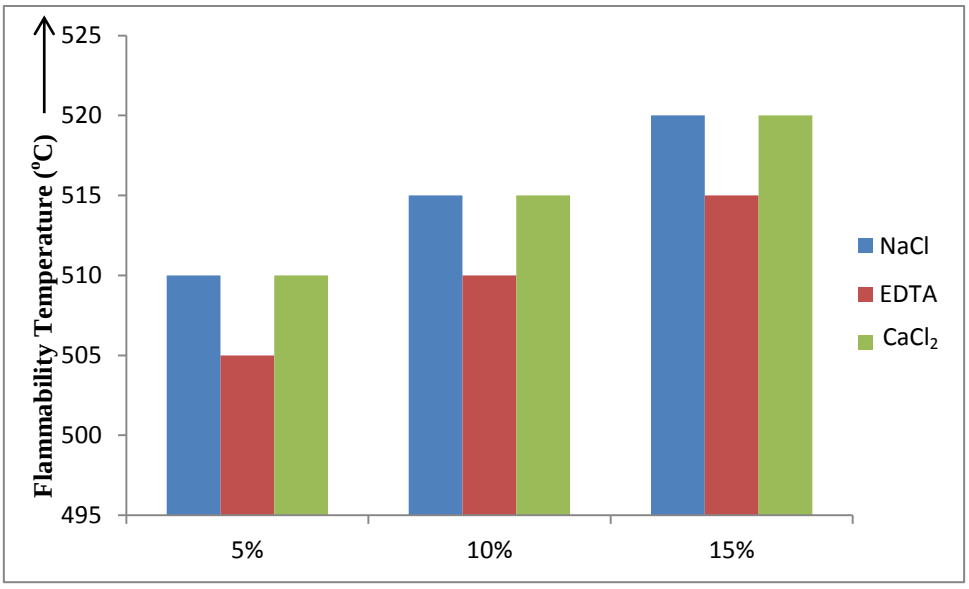

Fig A-6. Effect of different inhibitors on Flammability Temperature of MCL - 4

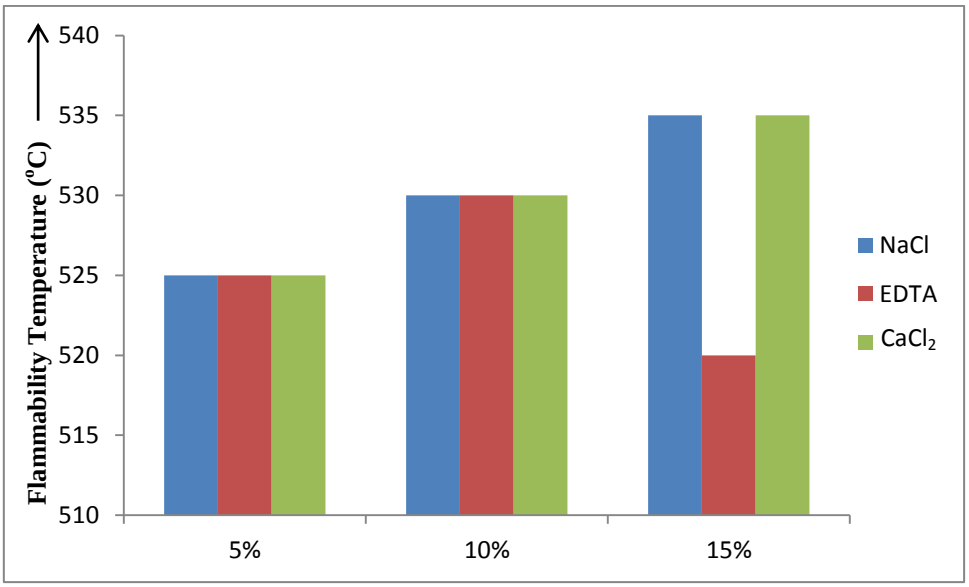

Fig A-7. Effect of different inhibitors on Flammability Temperature of MCL - 5

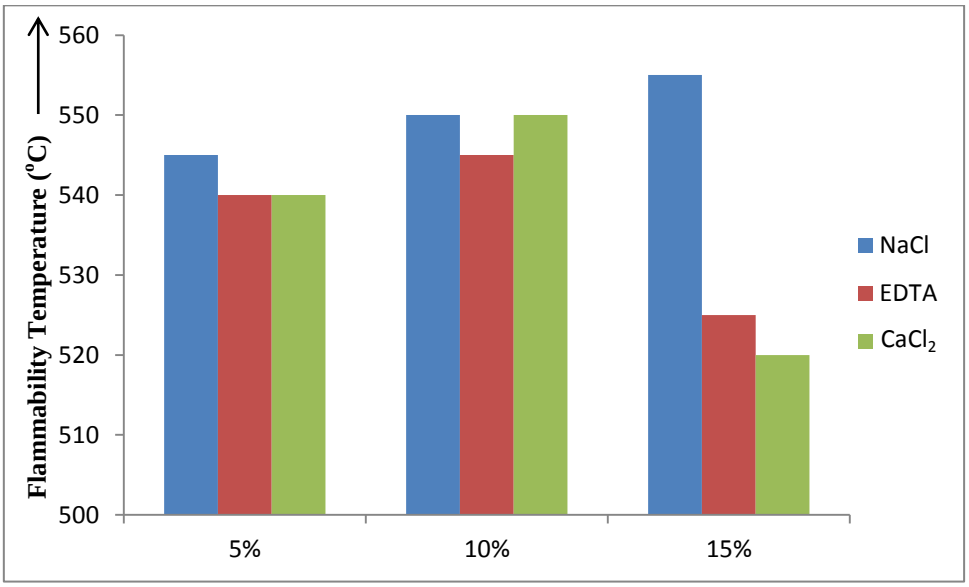

Fig A-8. Effect of different inhibitors on Flammability Temperature of MCL - 6

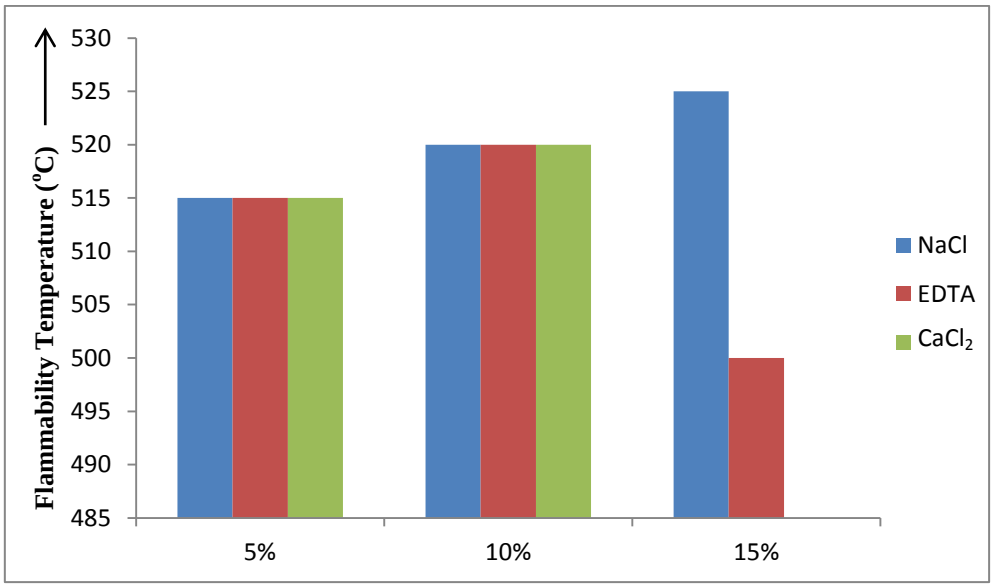

Fig A-9. Effect of different inhibitors on Flammability Temperature of MCL - 7

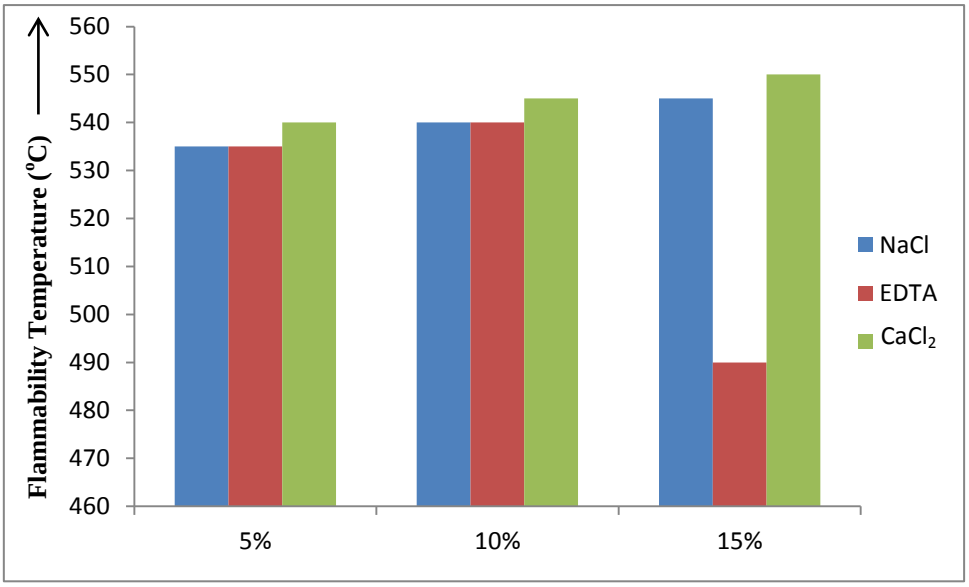

Fig A-10. Effect of different inhibitors on Flammability Temperature of MCL - 8

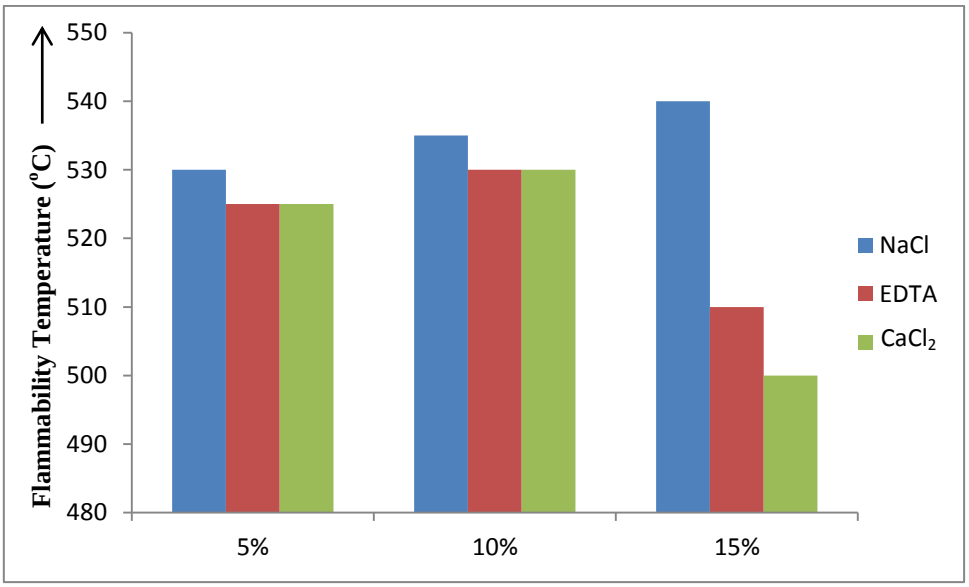

Fig A-11. Effect of different inhibitors on Flammability Temperature of NEC - 1

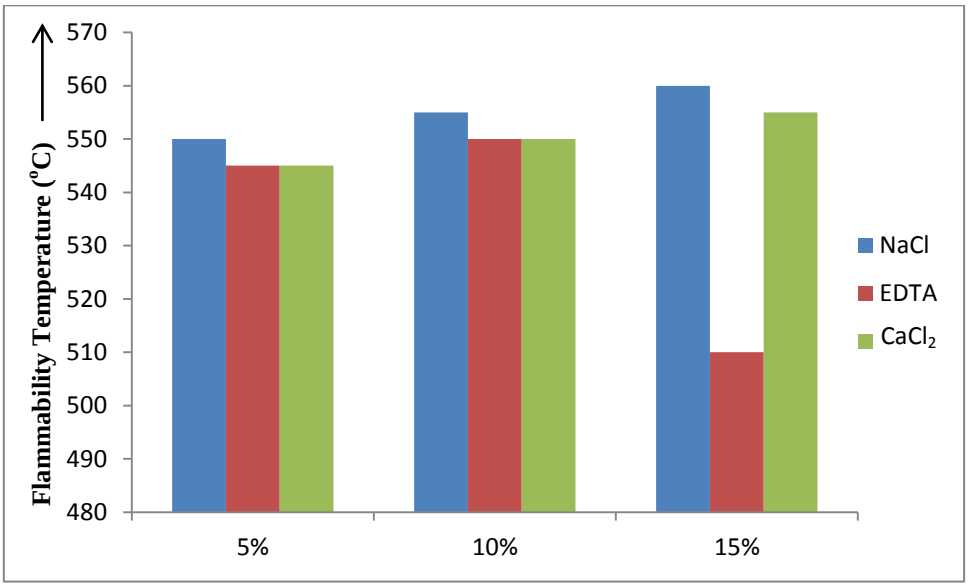

Fig A-12. Effect of different inhibitors on Flammability Temperature of NEC - 2

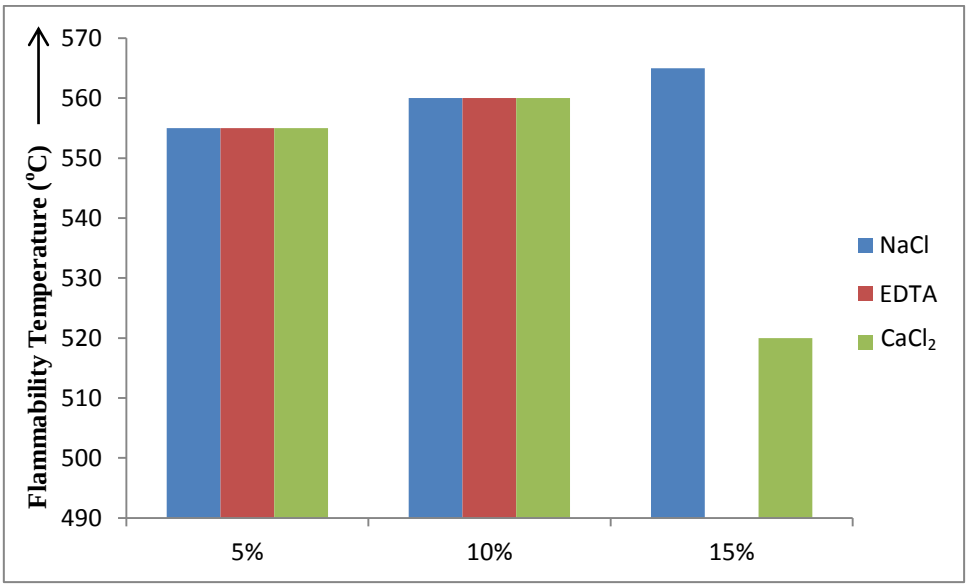

Fig A-13. Effect of different inhibitors on Flammability Temperature of NEC - 3

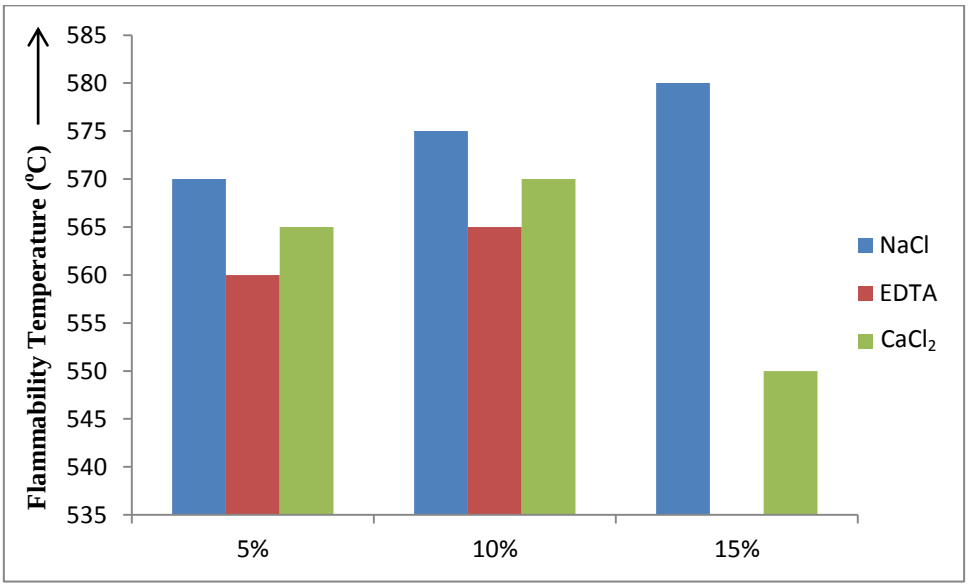

Fig A-14. Effect of different inhibitors on Flammability Temperature of NEC - 4

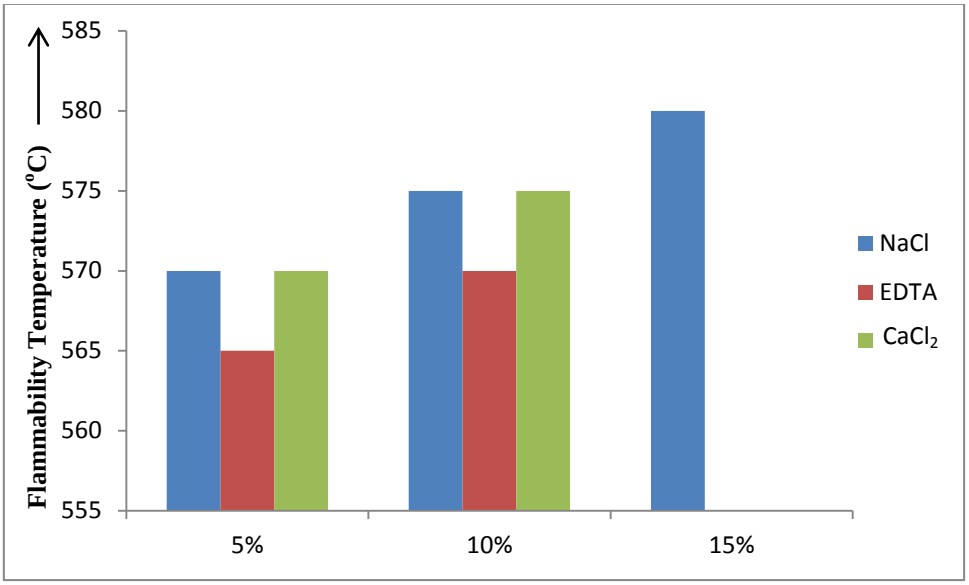

Fig A-15. Effect of different inhibitors on Flammability Temperature of NEC – 5

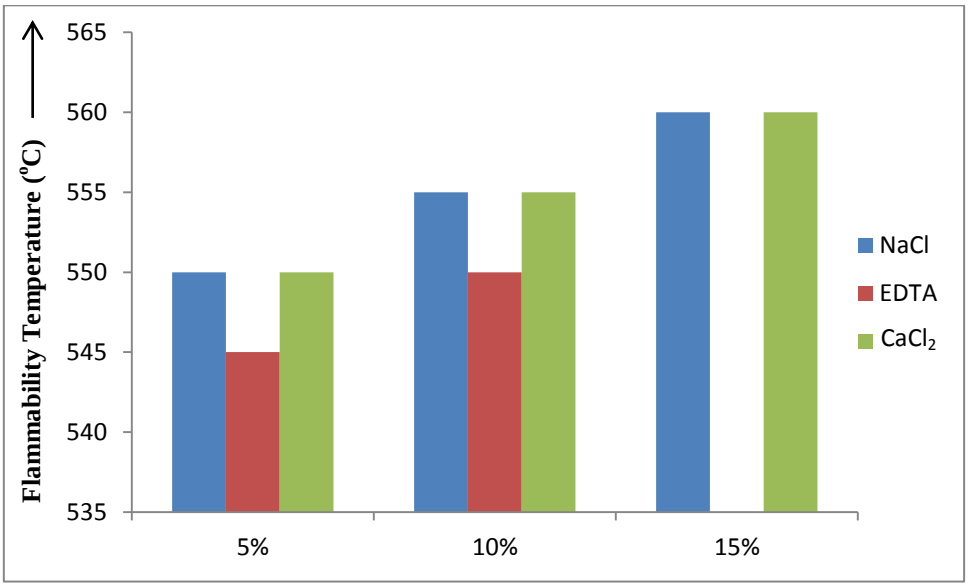

Fig A-16. Effect of different inhibitors on Flammability Temperature of NEC - 6

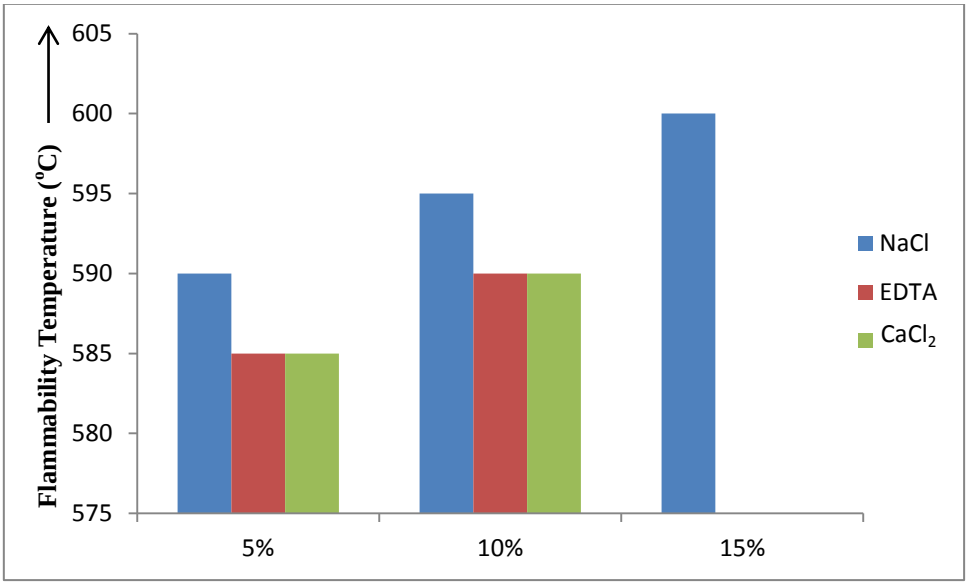

Fig A-17. Effect of different inhibitors on Flammability Temperature of IISCO - 1

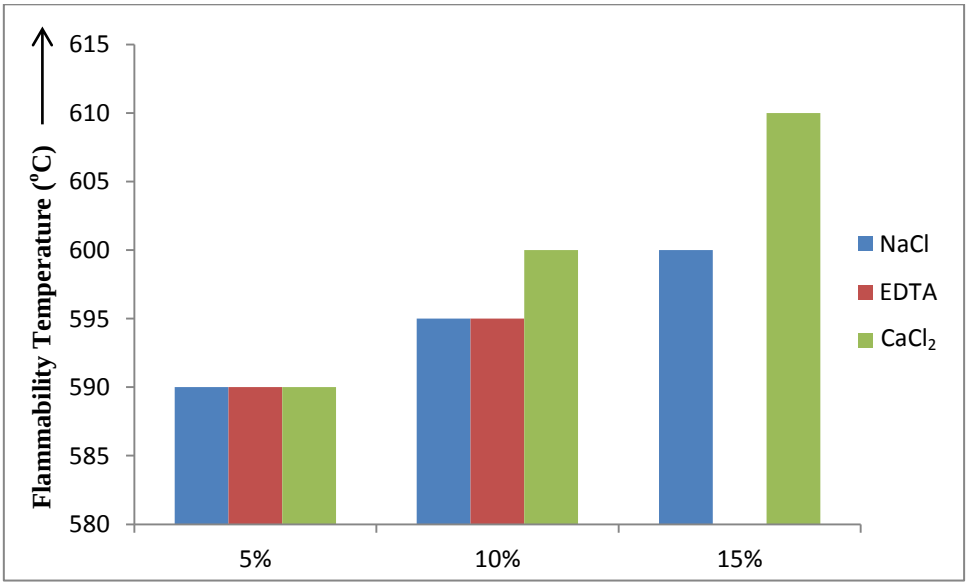

Fig A-18. Effect of different inhibitors on Flammability Temperature of IISCO - 2

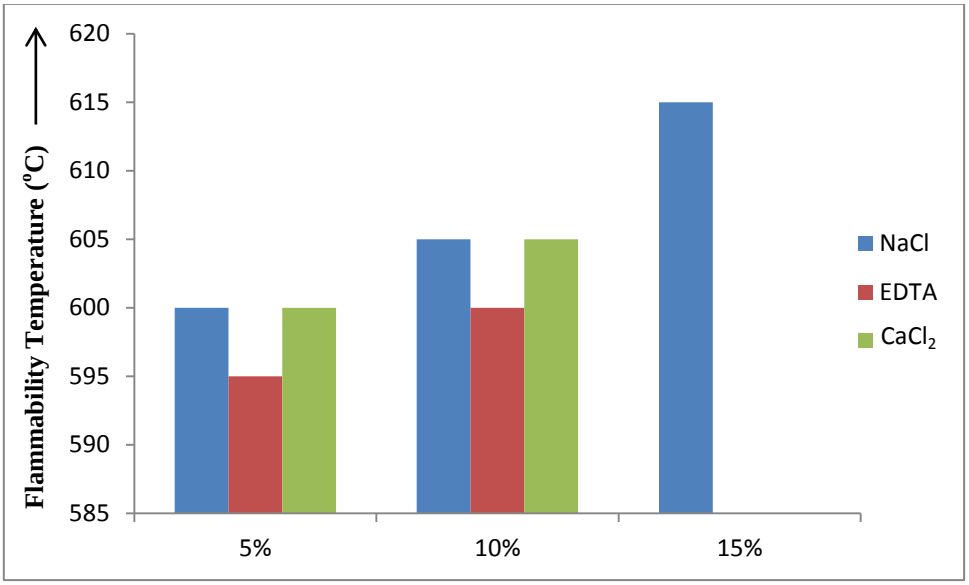

Fig A-19. Effect of different inhibitors on Flammability Temperature of BCCL - 1

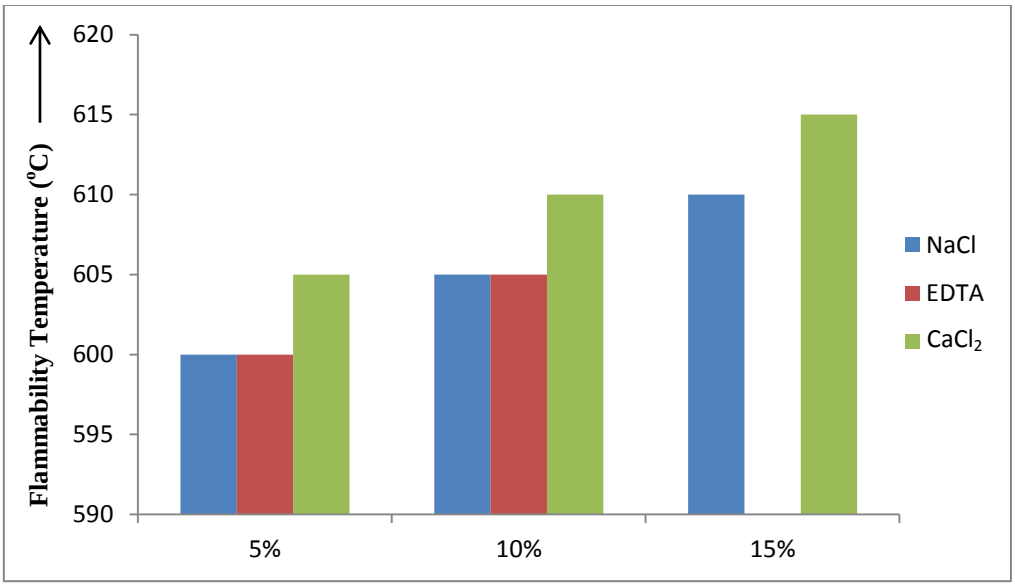

Fig A-20. Effect of different inhibitors on Flammability Temperature of TISCO - 1